



RESEARCH DEPARTMENT

REPORT

Ground-wave propagation in a realistic terrain

J.H. Causebrook, Ph.D., B.Sc., C.Eng., M.I.E.E.

B. Tait, B.Sc.

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Summary

LF and MF ground-wave propagation over a realistic terrain has been found to be very different to that over an assumed smooth earth. This report describes the basic nature of these differences, which include a non-simple relationship for field variation with distance and a non-free-space relationship between electric and magnetic fields. The theory of why these effects occur is summarized, and the measurements taken to demonstrate their nature are given. Also a description is given of a computer calculation method which has been devised to make use of the new knowledge.

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GROUND-WAVE PROPAGATION IN A REALISTIC TERRAIN

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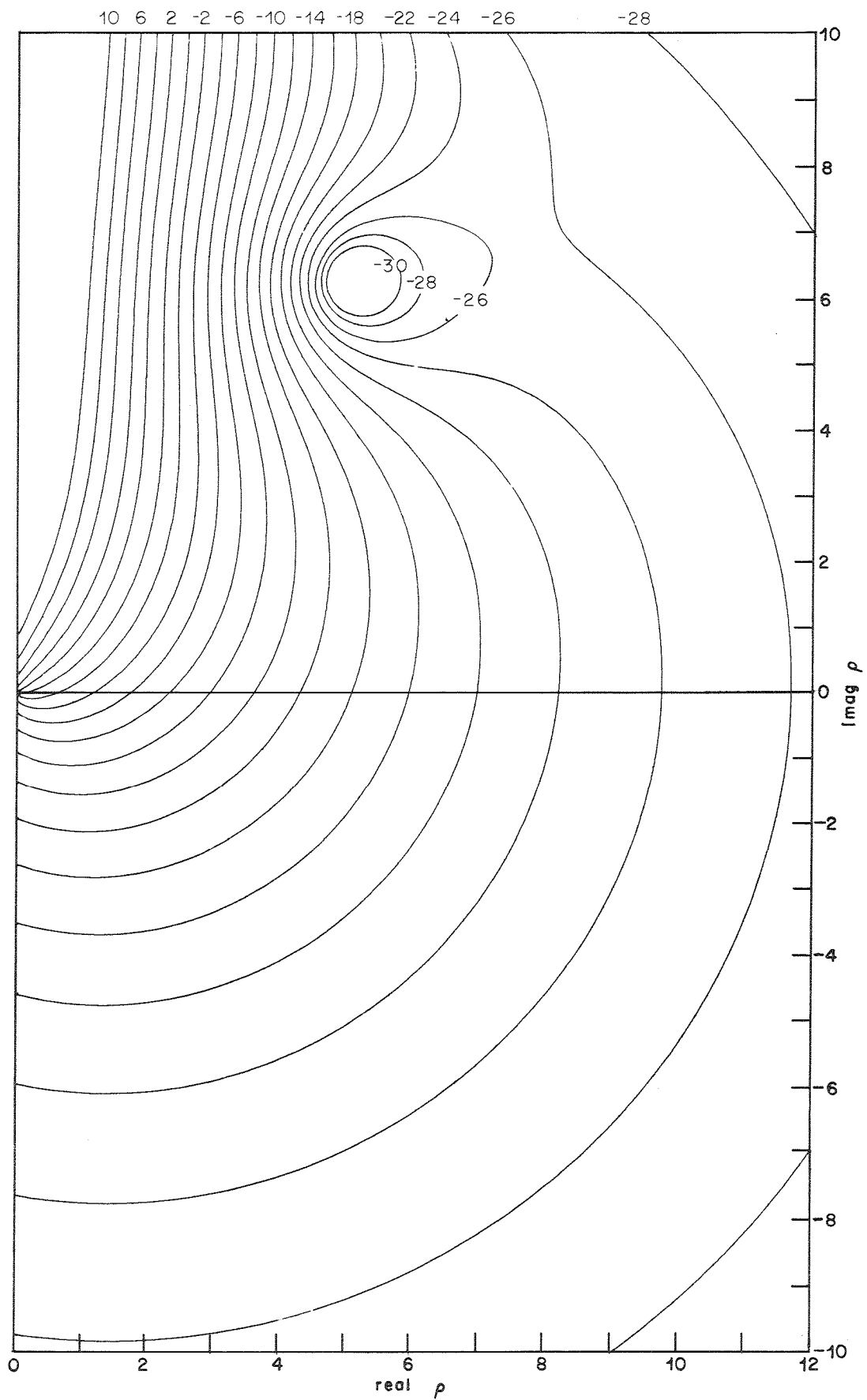


Fig. 1 - A mapping of the groundwave attenuation on an Argand diagram of the parameter $\rho = -j\pi\eta^2 r/\lambda$. The values of the contours are dB relative to a perfectly conducting plane

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List of principal symbols

η	surface impedance relative to the intrinsic impedance of free space
σ	conductivity (siemens/metre)
ϵ	dielectric constant
λ	wavelength (metres)
η_s	relative surface impedance for a smooth uncluttered earth
J	current density (amps/sq. metre)
E	electric field strength (volts/metre)
S	effective complex conductivity (siemens/metre)
h	height of clutter (metres)
u	dummy variable used in integration (see Equation (4))
m	number of unipoles per square metre (see Equation (5))
Z_o	characteristic impedance (ohms)
n	number of trees per square metre (see Equation (6))
R	resistance per metre (ohms/metre)
η_b	relative impedance of a perfectly conducting surface containing hemispherical bosses (see Equation (7))
F	fraction of area filled by a hemispherical boss
ρ	a parameter used to calculate surface wave attenuation (see Fig. 1) $\rho = -j\pi\eta^2 r/\lambda$
r	distance from transmitter to receiver (metres)
H	magnetic field strength (amps/metre)
P_b	percentage of ground covered by buildings
P_t	percentage of ground covered by trees
x_1, x_2, x_3	constants in Equation (12) determined by empirical means

1. Introduction

This report summarizes results of investigations into ground-wave propagation in a realistic terrain. The work was carried out in the l.f. and m.f. broadcast bands, i.e. 150 kHz to 285 kHz and 525 kHz to 1605 kHz. The investigation began because of poor coverage by a few transmitters in urban areas, but the scope widened when it was found that propagation in a realistic terrain differs significantly in important respects from the conventional theoretical model.

A report¹ and an IEE paper² described the effects of a built-up area on the magnetic field component from an m.f. broadcast station, and electric/magnetic field ratios were discussed in Electronics Letters.³ References 1 and 2 give the results of a measurement campaign in London, showing a surprising field strength distance relationship. The explanation of this was shown to be that metallic structures considerably modified the surface impedance to a value which could not be obtained on a smooth earth. The theory worked out for this indicated that in clutter the mean value of the ratio of electric to magnetic field would not be as in free space. This was later proved by measurement and published in Reference 3.

The recent work has increased the amount of measured evidence to include a greater variety of areas and frequencies. In particular the effect of wooded areas has been studied. Some refinements have been made to the theory, and to the method of calculation which allows for the realistic terrain.

A receiver, aerials and analysing equipment were made for the measurements. These enabled continuous recordings and statistics of fields to be taken on the move in a car. In addition it was possible to make quick changes of the received frequency and the aerials (from electric to magnetic detectors). Other reports will be published to describe this equipment.

2. Theory

The field at a point is a function of the relative surface impedance values, η , existing between transmitter and receiver. For a smooth earth, conductivity σ (siemens/metre), dielectric constant ϵ and wavelength λ (metres) the surface impedance effective at grazing incidence is

$$\eta_s = \frac{[\epsilon - j60\sigma\lambda - 1]^{1/2}}{\epsilon - j60\sigma\lambda} \quad (1)$$

Values of σ and ϵ are given by Terman⁴ for different types of terrain. With the relative magnitudes quoted it is sufficient for our case to take

$$\eta_s \simeq (60\sigma\lambda)^{-1/2} e^{j\pi/4} \quad (2)$$

The error of this approximation is numerically insignificant compared with that due to the assumption of a smooth earth.

In a realistic terrain, containing buildings, trees, surface irregularities etc., a vertical current density, J , will be induced by the electric field, E . Thus we can think of an effective complex conductivity, vertically, being given by:

$$S = \frac{J}{E} \quad (3)$$

At the top of the clutter, height b , a value for surface impedance was derived in Reference 1. This may be written as:

$$\eta = \eta_s + \frac{j2\pi b}{\lambda} \left[1 - \int_0^1 \frac{du}{1 - j60\lambda S(u)} \right] \quad (4)$$

where the dummy variable u ranges from the base of the irregularities to the top. S is written as a function of u because it may vary with height. This leaves the problem of giving values to S in the practical cases. For this purpose we made three categories.

- a) Highly conducting earthed unipoles, of less than quarter of a wavelength high, were given the values

$$S = j \frac{\pi m b^2}{\lambda Z_0} u \quad (5)$$

where Z_0 is the characteristic impedance⁵ of the unipole and m is the number of them per square metre.

- b) For resistive objects such as trees:

$$S = \frac{n}{R} \quad (6)$$

where R is the resistance per metre and n is the number per square metre.

- c) For terrain undulations it is useful to consider an analysis by Wait^{6,7} of propagation over hemispherical bosses of finite conductivity sitting on a perfectly conducting plane.

This work gives results of the form:

$$\eta_b = \frac{2\pi b j}{\lambda} F W \quad (7)$$

where b is the radius of the bosses (or height above the plane). F is the fraction of area filled and W is a complex number which has a real part at least 6 times larger than the imaginary and is a function of the ratio of skin depth to radius of boss.

The analogy to undulating terrain is weak in two respects: the plane is not perfectly conducting but has surface impedance η_s and hills unlike bosses have a height much less than their base radius. However, the analysis does suggest a reasonable answer might be given by:

$$\eta = \eta_s + j b \frac{2\pi}{\lambda} y \quad (8)$$

where y is a real number approximately equal to $1/2$.

The result obtained in Equation (8) is in keeping with the other equations for clutter and with other types of reasoning. It is equivalent to saying that:

$$S = \frac{jC}{60\lambda} \quad (9)$$

where C is approximately equal to one.

In many cases the term added to the smooth earth surface impedance, because of the cluttered and irregular nature of the terrain, is sufficient to radically change the field levels. In fact the whole form of the field strength/distance relationship may be altered as can be seen from Fig. 1. Here use is made of the fact that surface wave attenuation can be calculated via a complex variable we call ρ . This variable can be formed from the basic parameters of surface impedance, distance and frequency as follows:

$$\rho = -j\pi\eta^2 r/\lambda \quad (10)$$

The plot is then a mapping of the magnitude of attenuations on the complex plane ρ . Thus a straight line from the origin corresponds to a radial line from the transmitter for homogeneous ground constants; distances on the diagram are then proportional to distances from the transmitter (r). For a smooth earth the relevant part

of the diagram is always just below the positive real axis. However, with the surface impedance of a realistic terrain many results will be obtained from the upper region of the plot. Here changes in field value are more drastic.

As well as obtaining a result for surface impedance, the theory developed in Reference 1 gave a result for the electric to magnetic field

ratios in the realistic terrain.

$$\frac{E}{H} = \frac{120\pi}{1 - j60\lambda S} \quad (11)$$

For a propagation path that changes significantly along its length a method of calculation is required which readily allows for changes of



Fig. 2 - Sketch map of the London Area

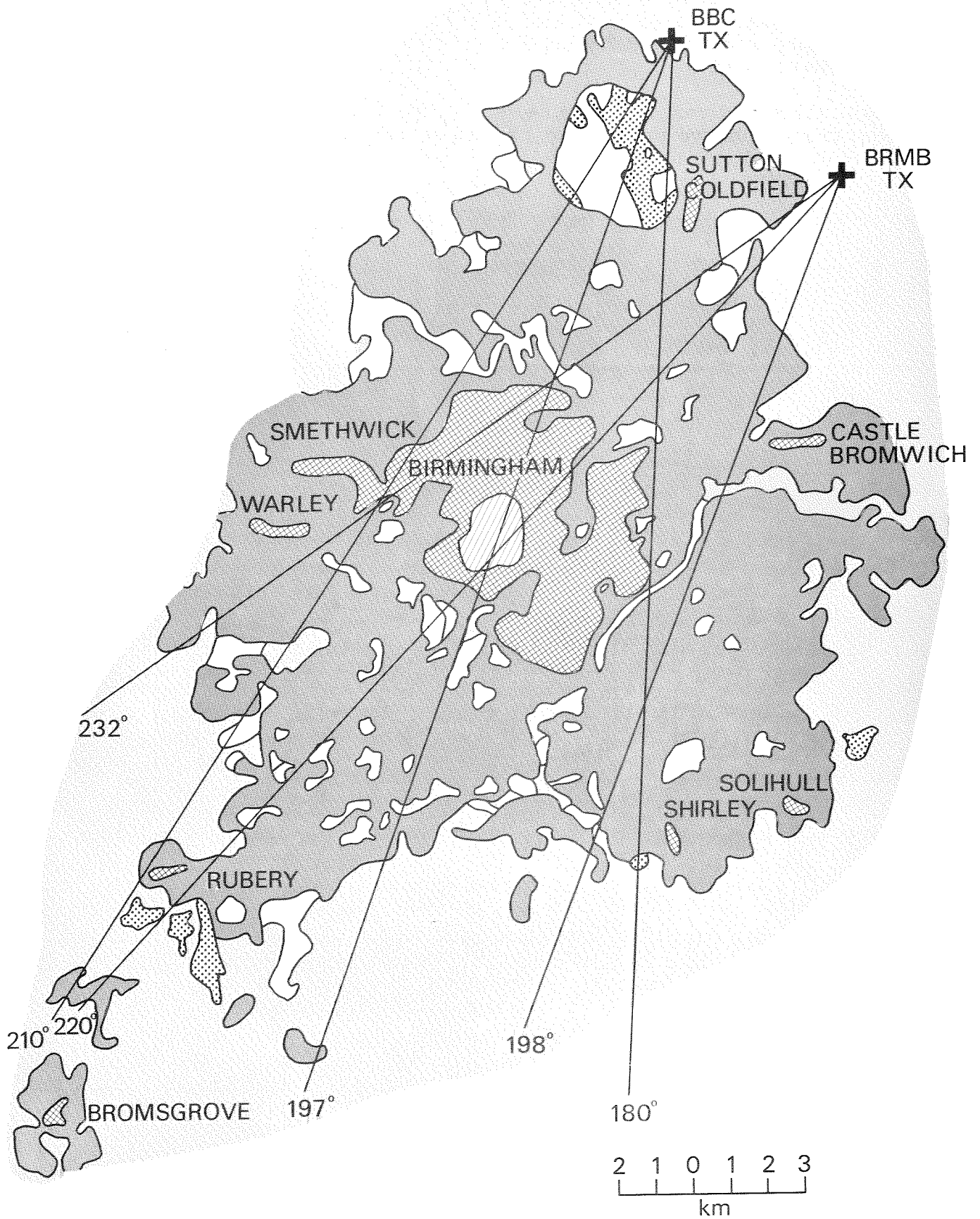


Fig. 3 - Sketch map of the Birmingham Area

surface impedance. This may be achieved by an integral equation method of field calculation, also described in Reference 1.

With this theory it is possible to attempt field calculations for a realistic terrain. However, certain quantities are still rather nebulous and it is left to the following empirical work to put these on a firmer basis.

3. The measurements

The measurement campaigns were organized to cover the frequency range and include a variety of terrain, with particular emphasis on that terrain where the most dramatic effects might be expected. The frequencies measured were 200, 526.5, 692, 908, 1151, 1214 and 1457 kHz. The areas selected for measurement were London, Birmingham, the New Forest, a radial from Droitwich to Hastings (on the South-East coast) and a small circular tour in Surrey. In each case both the electric and magnetic fields were measured. Fig. 2 is a sketch map of the London area showing

two radials from the Brookman's Park transmitter along which many measurements were concentrated. Also shown is part of the radial from the Droitwich transmitter to Hastings and a route taken to produce demonstration charts. Fig. 3 is a sketch map of the Birmingham area showing three radials from the BBC transmitter (Sutton Coldfield) and another three from the independent local radio transmitter called BRMB (Langley Mill), measurements being as close to the radials as roads permitted. Fig. 4 is a sketch map of the New Forest area showing the route taken when measuring the Bartley transmitter. Table 1 shows the way in which the 'clutter' is marked on these maps.

The way in which to present the measured and calculated results gave us some difficulty. The points which went into our decision were:

1. We wished to draw attention to the difference from the free space ratio which existed in the ratio of electric to magnetic field. (Conventional measuring methods added a confusion here because receivers usually express

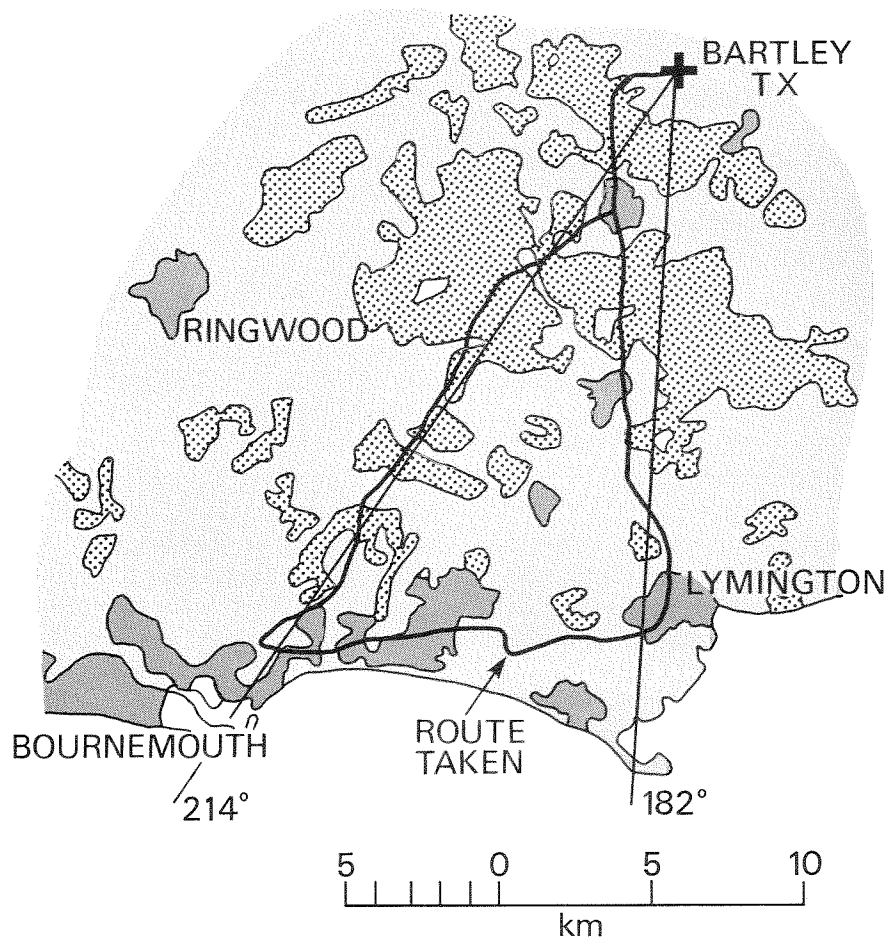
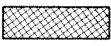
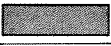
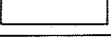


Fig. 4 - Sketch map of the New Forest Area

TABLE 1

Topographical categories

Type of Area	Class	% of ground cover	Height (m) of clutter	Shading on maps
City centres	A	30	20	
Town centres	B	20	15	
Suburban	C	15	10	
Semi-Rural	D	10	10	
Wooded	F	10	15	
Bare	Blank	0	0	

results in $\mu\text{V/m}$ even though they detect magnetic field.)

2. We wished to emphasize the attenuation of field relative to that which would be obtained over a perfectly conducting plane earth. (To include the perfectly conducting plane-earth attenuation in our plots would make the particular points of concern less clear.)
3. We could not accurately find the absolute value of the field over a perfectly conducting plane earth, from a given transmitter, unless parameters such as aerial efficiency could be determined.

These points led us to choose a presentation which means that on the plots described below, electric field is expressed as $20 \log_{10}(Er)_{\text{mV}}$ and magnetic field as $20 \log_{10}(120\pi Hr)_{\text{mV}}$ where r is the distance from transmitter to receiver.

Fig. 5 is a plot of measurements from the Brookman's Park transmitter. The crosses and squares are median values for 500 metre stretches, for magnetic and electric fields respectively. The results are not like those obtained over a smooth earth, even if changes of conductivity were included. They do, however, follow a trend that would be obtained if, from Fig. 1, a line were considered which went from the origin and passed near the 'hole'.

The electric and magnetic fields are both plotted in terms of millivolts per metre, assuming the free space ratio to obtain a direct comparison. It can be seen that the electric field has a strong

tendency to be a lower value, this tendency increasing with the amount of clutter.

Fig. 6 is a plot of measurements obtained in Birmingham from the BBC transmitter (1457 kHz) and the BRMB transmitter (1151 kHz). The measurements taken from the BBC site show similar trends to London results, but from the BRMB site there is not such a dramatic change with distance. This is attributed to the lower frequency and to the fact that the BRMB site is more suited to serve the town centre.

Fig. 7 is a plot of measurements from the Bartley transmitter (692 kHz) taken through the New Forest. These were taken to check the theory about the tree effects; unfortunately the New Forest is not sufficiently dense and extensive to give very dramatic results.

Fig. 8 is a plot of measurements from the Droitwich transmitter (200 kHz) along a radial line ending in Hastings on the South-East coast. The main points to be noted here are that the magnetic field decays little from the perfectly conducting earth value and the electric field is generally lower than this magnetic field value. The smooth earth calculation would give greater attenuation of the magnetic field with distance and does not predict the relatively reduced electric field.

The theory indicates that there is no frequency factor in the relative depression of the electric field due to vertical metallic structures. To test this theory, 200 kHz from the Droitwich transmitter was also measured on the routes from

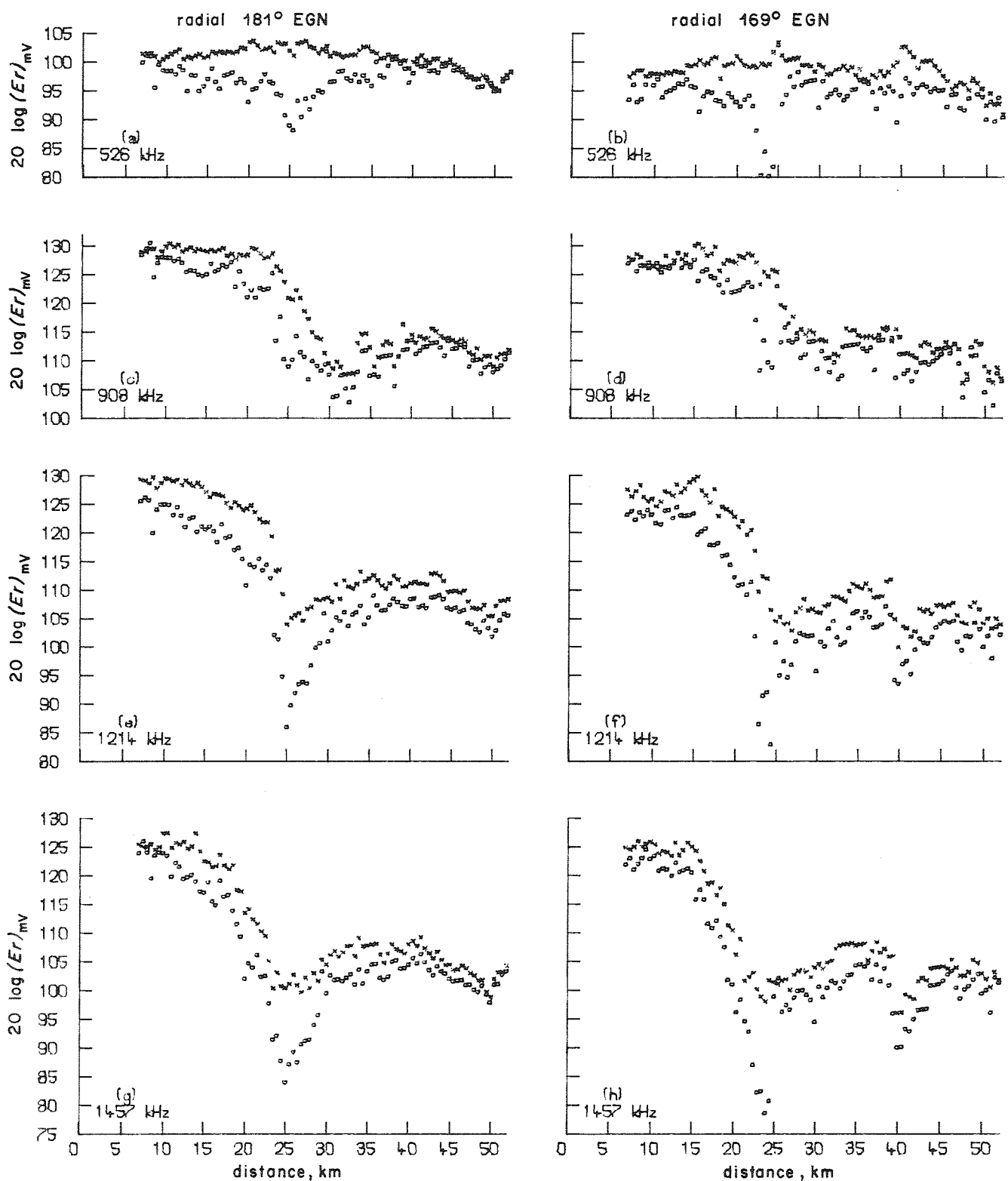


Fig. 5 - Measurements through London from the Brookmans Park transmitter

x Magnetic field

□ Electric field

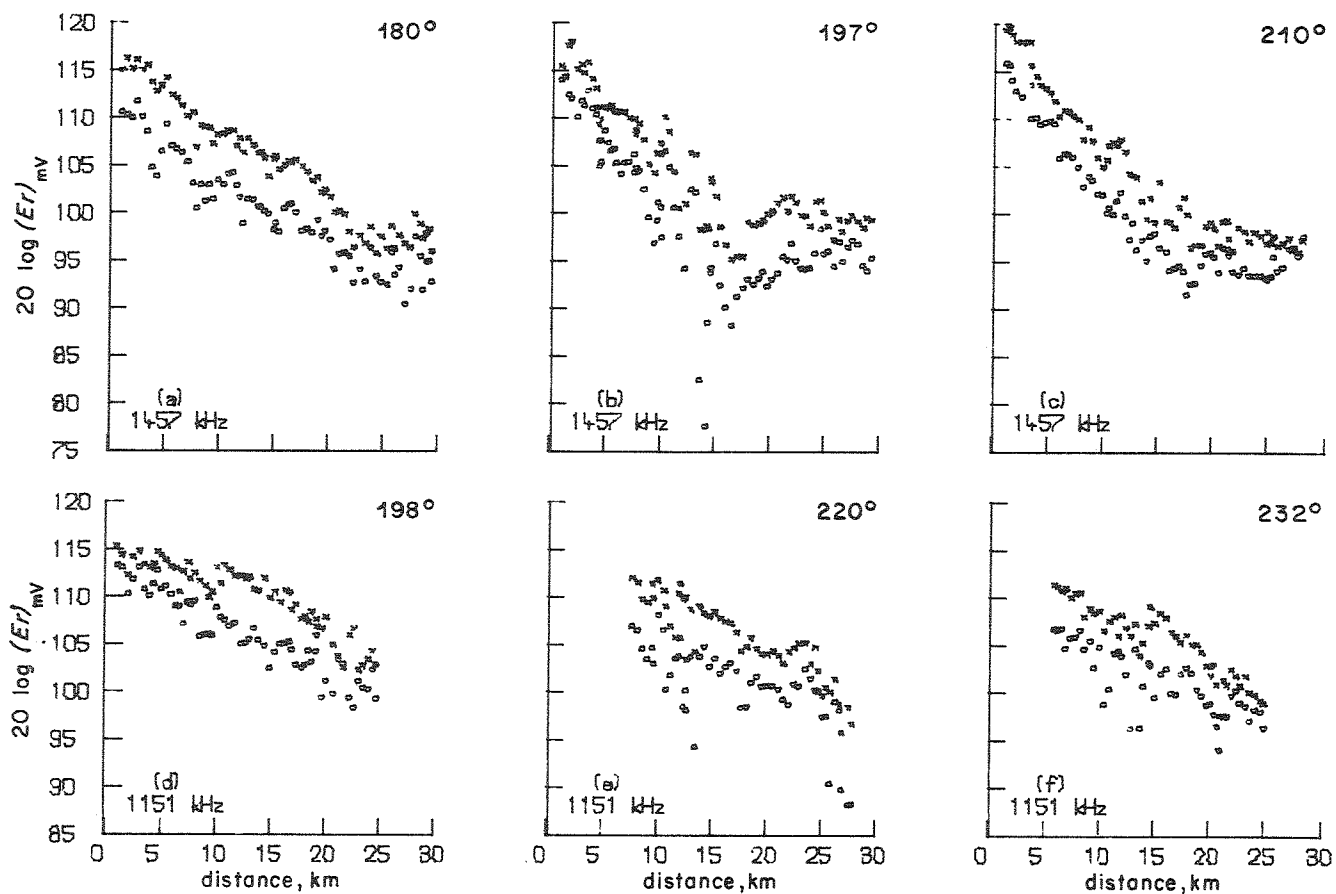


Fig. 6 - Measurements taken in the Birmingham Area

x Magnetic field

□ Electric field



Fig. 7 - Measurements taken through the New Forest

x Magnetic field

□ Electric field

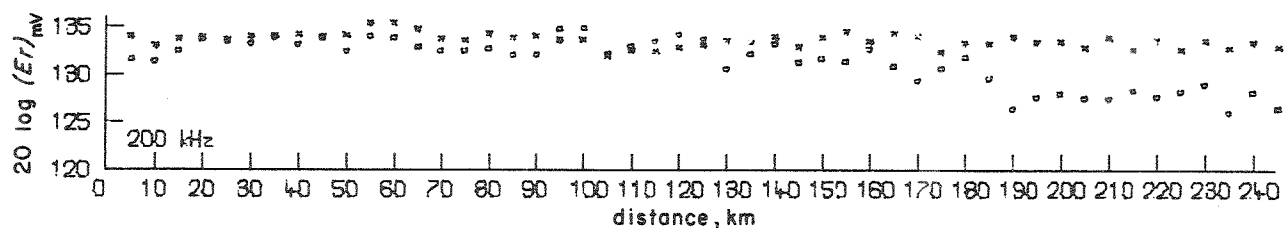


Fig. 8 - Measurements taken from Droitwich to the South-East coast

x Magnetic field

□ Electric field

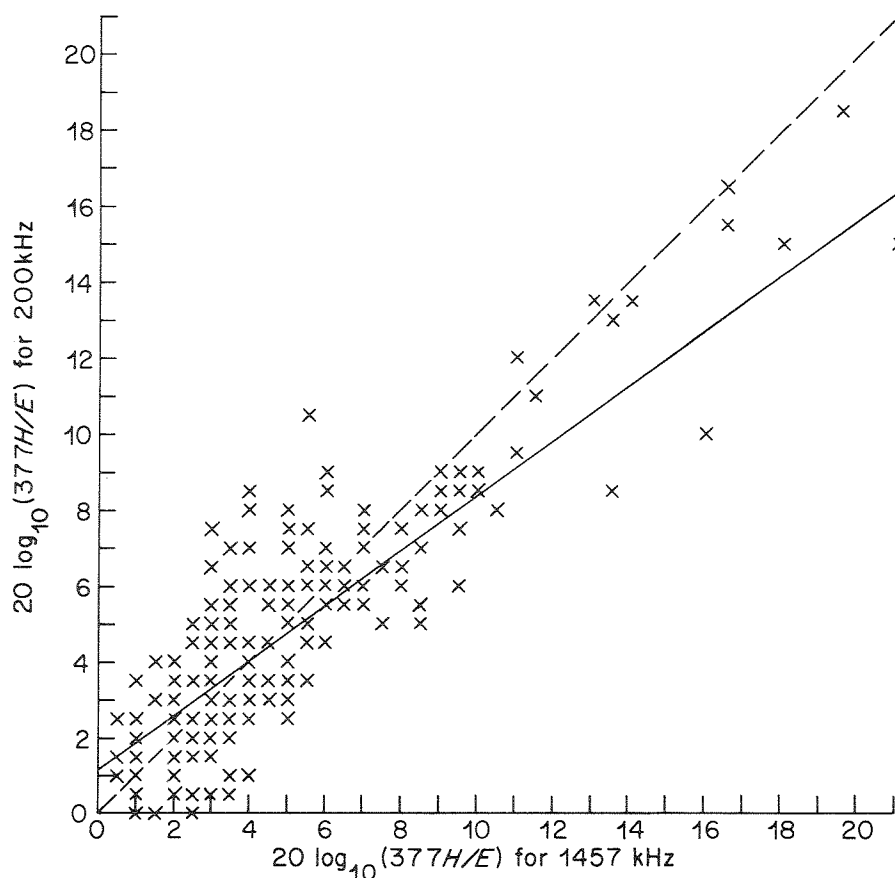


Fig. 9 - Comparing the relative reduction of electric field on 200 and 1457 kHz

the Brookman's Park transmitter through London. The plot of Fig. 9 was then made; in this the crosses result from the analysis of measured results and a regression line (solid) was compared to a 45° line (dashed). It can be seen that the theory and measurements are in reasonable agreement.

Fig. 10 gives examples of pen recordings taken on the route in Surrey (see Fig. 2). The figure attempts to show, on short pieces of chart, as many features as possible but not extreme cases (the town included is not heavily built up with tall buildings). On Fig. 10(a) the route first crosses a motorway intersection, then descends a steep hill with a high footbridge crossing near the top. The town centre is at the foot of the hill. The sharp drop-out of electric field occurs when passing through a narrow section of street. Fig. 10(b) was recorded in an area that is sparsely built-up, with an uphill route and other features as marked. The high spikes of field on the 1457 kHz electric-field trace are associated with overhead power lines. The wooded area has the greatest effect on the 200 kHz electric field, which again supports the theory i.e. vertical resistive objects have a frequency dependence such that lower frequencies have

the greater attenuation.

It was suspected that the attenuation of electric field caused by trees would be less in winter because of the reduction in sap resulting in an increase in resistance. Therefore, the tour was redone in winter and the hypothesis confirmed. In particular, the 200 kHz section of chart marked 'heavy tree cover' showed an increase of the electric field of about 2.5 dB. Of course, this could be attributed to the lack of leaves, but the theory indicated that the total tree resistance is the important factor.

4. The calculation system

The measurements obtained have supported the theory put forward, but they must do more than that because it is not practicable to obtain all the required quantities from theory. A further practical point is that even though some parameters may be reasonably estimated it may be very time consuming and costly to do so. For a calculation system to be of value it must either do something that cannot be done by measurement or it must do it quicker, cheaper and without

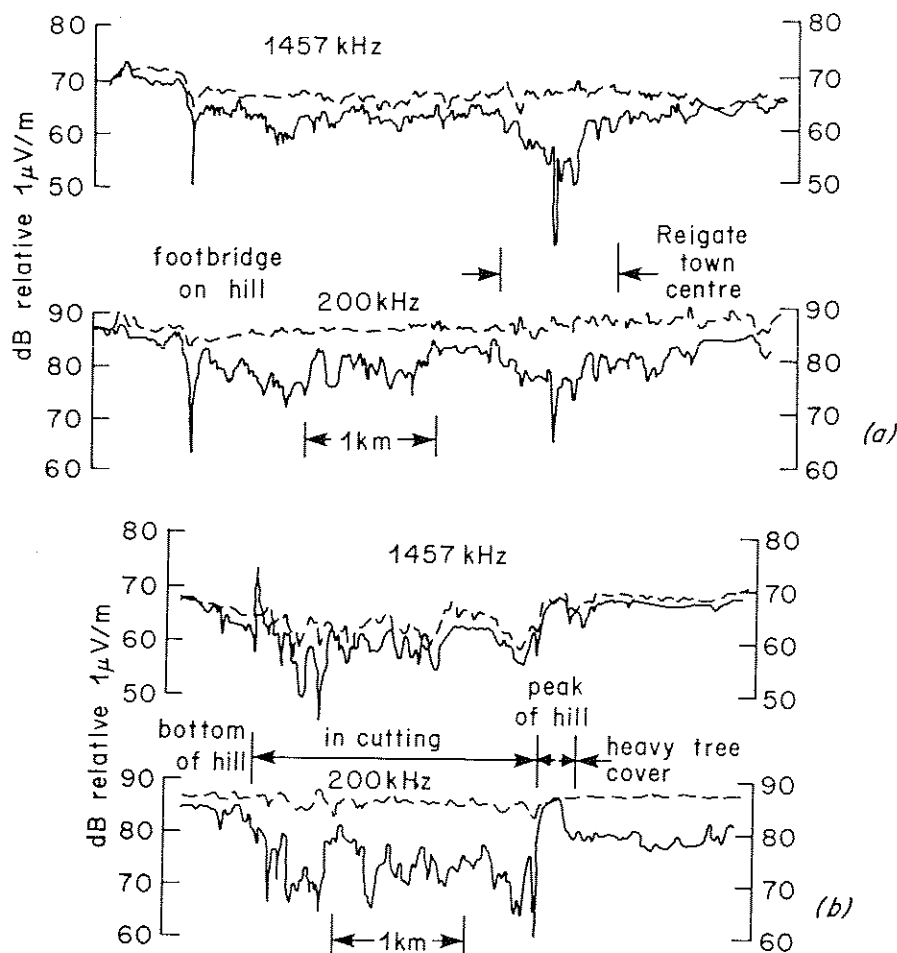


Fig. 10 - Pen traces of field variations

----- Magnetic field ————— Electric field

requiring excessive amounts of skill and knowledge from the user. With these thoughts in mind the topographical categories of Table 1 were devised and assigned as shown in Figs. 2 to 4. This reduces to a minimum the amount of data required from the user, about clutter.

For each of a series of $\frac{1}{2}$ km squares along the radial line we give the '% of ground cover' by buildings the symbol P_b and by trees P_t . Then using the information contained in Equations (5) and (6) we get:

$$60\lambda S(u) \approx \lambda(x_1 P_t + x_2 P_b) + jx_3 P_b u \quad (12)$$

where x_1 , x_2 and x_3 are to be determined by empirical means.

The value of x_1 was determined by actual measurement of the resistance of trees and found to be approximately 12×10^{-5} . The values of x_2 and x_3 were determined so that the London measurements were calculated with a minimum of error. This resulted in x_2 being given the value

165×10^{-8} and x_3 equalling 2.5×10^{-2} .

For the determination of electric field via Equation (11) it is not sufficiently accurate to use the percentage of ground cover given in Table 1. These figures are averages over large areas, but the electric field is modified in a way which is very dependent on the immediate surroundings. Thus if a measurement is taken in parkland the ratio of electric to magnetic fields will be close to that of free space. However, in a highly built-up street the electric field is reduced to a greater degree than the figures of Table 1 would give. Our measurements were taken driving down such streets and it was found that by doubling the ground cover values in Table 1 fairly accurate predictions of these electric fields were obtained. This extra problem associated with electric field will make its accurate prediction more difficult than that of predicting the magnetic field.

The data for a calculation was then as shown in Fig. 11, together with explanations of the various items of data required. The data for

B.P.	LON	181	DEG	>	label
52.0				>	length of radial (kms)
0.0		130		}	terrain profile : distance (kms) and height (m)
6.0		100			
7.0		100			
8.0		100			
20.0		50			
29.5		0		}	from 0 to 52 kms conductivity is 10 mS/m
40.0		50			
43.0		100			
45.0		150			
52.0		200			
52.0		10		}	clutter data : start of range (kms), clutter type, end of range (kms)
0.0	D	0.6			
0.6	C	1.5			
1.5	D	2.5			
2.5	C	3.5			
3.5	R	4.5			
4.5	C	4.8			
4.8	D	6.5			
6.5	C	7.7			
7.7	F	8.0			
8.2	C	12.5			
12.5	R	20.7			
20.7	A	32.0			
32.0	R	36.3			
36.3	C	39.5			
39.5	R	43.3			
44.3	C	46.0			
47.5	C	49.5			
49.5	D	52.0			

Fig. 11 - Data for input to Computer Program

height of terrain is of little importance but is included for the sake of completeness.

An example of the print-out of results is shown in Fig. 12. The output gives the wavelength in metres, labelled as 'LAMBDA(M)'. The columns are as follows.

1. The distance of field point from transmitter in metres.
2. The terrain height in metres.
3. The average height assumed for clutter in metres.
4. The percentage of area covered by buildings.
5. The percentage of area covered by trees.
6. The ground conductivity in millisiemens per metre.
- 7 & 8. The surface impedance, η , including the clutter factor as defined in Equation (4).
9. The magnitude of the loss of the magnetic field relative to a perfectly conducting flat surface.

10. The phase of the loss factor.
11. Column 9 expressed as dB.
12. $20 \log_{10}(120\pi H \times \text{distance})_{mV}$. The reasons for choosing this representation are given in Section 3 above.
13. This gives a figure for the additional loss (dB) of the electric field relative to the magnetic, i.e. $20 \log_{10}(120\pi H/E)$. In free space this value would be zero.

The calculations of magnetic field are plotted in Figs. 13–16 together with the measurements so that the degree of success may be assessed. In order to make a comparison between calculations and measurements it was necessary to assume a field value which would be obtained on a perfectly conducting earth from each transmitter. This was done by consideration of the transmitter characteristics and the field values close to the transmitter.

Fig. 13 shows the results from Brookman's Park on radials through London. The field trends

GROUND-WAVE BY INTEGRAL EQN. INCLUDING CLUTTER EFFECTS

LAMBDA(M)= 247

B.P. LON 181 DEG

DIST	HT	CHT	PB	PT	SIG	ETA	...	LOSS...	377HD	377H/E		
M	M	M	%	%	MS/M	REAL	IMAG	MAG	DEG	-DB	DB	DB
500	129	10	10	0	9	.063	.087	1.047	27	-.4	130.4	3.5
1000	127	10	13	0	8	.067	.098	1.055	41	-.5	130.5	4.3
1500	125	10	15	0	8	.067	.102	1.055	52	-.5	130.5	4.9
2000	122	10	10	0	9	.063	.087	1.025	58	-.2	130.2	3.5
2500	118	10	10	0	9	.063	.087	1.005	65	-.0	130.0	3.5
3000	115	10	15	0	8	.067	.102	1.004	73	-.0	130.0	4.9
3500	111	10	15	0	8	.067	.102	.983	80	.1	129.9	4.9
4000	108	15	20	0	8	.068	.136	1.014	92	-.1	130.1	6.0
4500	105	15	20	0	8	.068	.136	1.002	100	-.0	130.0	6.0
5000	102	10	13	0	8	.067	.098	.925	102	.7	129.3	4.3
5500	100	10	10	0	9	.063	.087	.889	104	1.0	129.0	3.5
6000	100	10	10	0	9	.063	.087	.865	107	1.3	128.7	3.5
6500	100	10	10	0	9	.063	.087	.845	110	1.5	128.5	3.5
7000	100	10	15	0	8	.067	.102	.832	115	1.6	128.4	4.9
7500	100	10	15	0	8	.067	.102	.811	120	1.8	128.2	4.9
8000	100	13	5	6	9	.114	.088	.687	126	3.3	126.7	2.0
8500	99	6	9	0	9	.063	.075	.692	123	3.2	126.8	3.2
9000	99	10	15	0	8	.067	.102	.701	129	3.1	126.9	4.9
9500	98	10	15	0	8	.067	.102	.687	132	3.3	126.7	4.9
10000	97	10	15	0	8	.067	.102	.667	136	3.5	126.5	4.9
10500	95	10	15	0	8	.067	.102	.648	140	3.8	126.2	4.9
11000	94	10	15	0	8	.067	.102	.629	143	4.0	126.0	4.9
11500	92	10	15	0	8	.067	.102	.608	147	4.3	125.7	4.9
12000	90	10	15	0	8	.067	.102	.588	150	4.6	125.4	4.9
12500	88	10	15	0	8	.067	.102	.570	153	4.9	125.1	4.9
13000	86	15	20	0	8	.068	.136	.579	161	4.7	125.3	6.0
13500	84	15	20	0	8	.068	.136	.563	166	5.0	125.0	6.0
14000	81	15	20	0	8	.068	.136	.541	172	5.3	124.7	6.0
14500	79	15	20	0	8	.068	.136	.520	176	5.7	124.3	6.0
15000	76	15	20	0	8	.068	.136	.495	182	6.1	123.9	6.0
15500	73	15	20	0	8	.068	.136	.472	186	6.5	123.5	6.0
16000	71	15	20	0	8	.068	.136	.449	190	7.0	123.0	6.0
16500	68	15	20	0	8	.068	.136	.425	194	7.4	122.6	6.0
17000	65	15	20	0	8	.068	.136	.402	198	7.9	122.1	6.0
17500	62	15	20	0	8	.068	.136	.380	201	8.4	121.6	6.0
18000	60	15	20	0	8	.068	.136	.359	204	8.9	121.1	6.0
18500	57	15	20	0	8	.068	.136	.338	208	9.4	120.6	6.0
19000	54	15	20	0	8	.068	.136	.318	210	10.0	120.0	6.0
19500	52	15	20	0	8	.068	.136	.299	213	10.5	119.5	6.0
20000	50	15	20	0	8	.068	.136	.280	216	11.1	118.9	6.0
20500	47	15	20	0	8	.068	.136	.262	218	11.6	118.4	6.0
21000	44	17	25	0	7	.074	.164	.253	225	12.0	118.0	7.0
21500	41	20	30	0	7	.074	.197	.244	236	12.3	117.7	8.0

Fig. 12 - Output of computer program

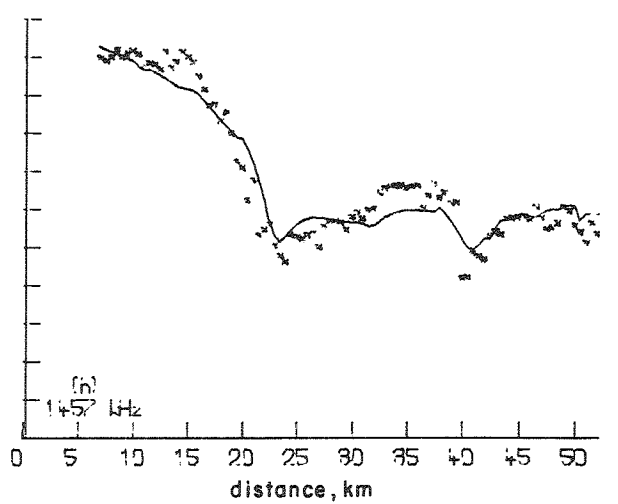
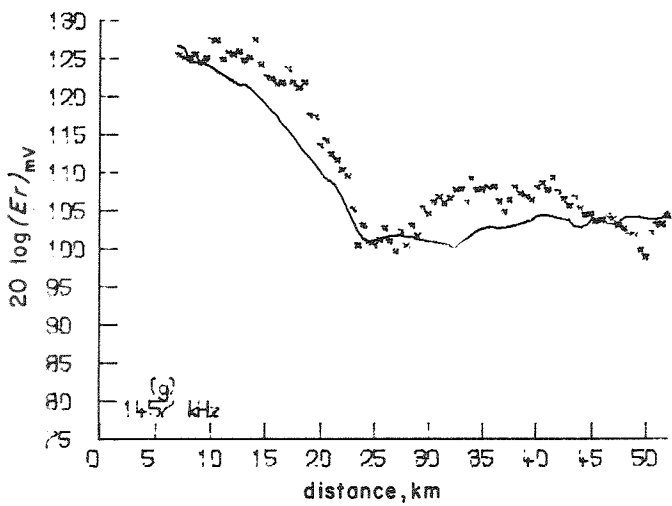
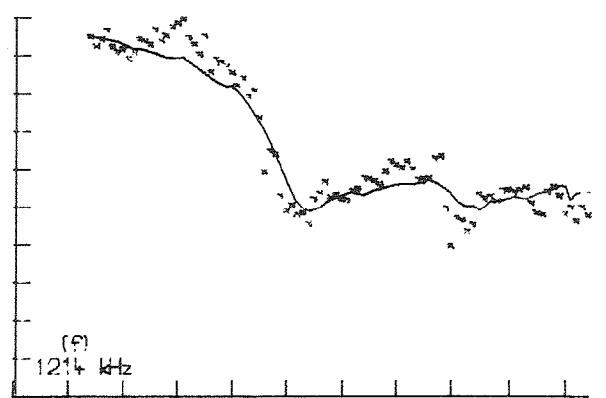
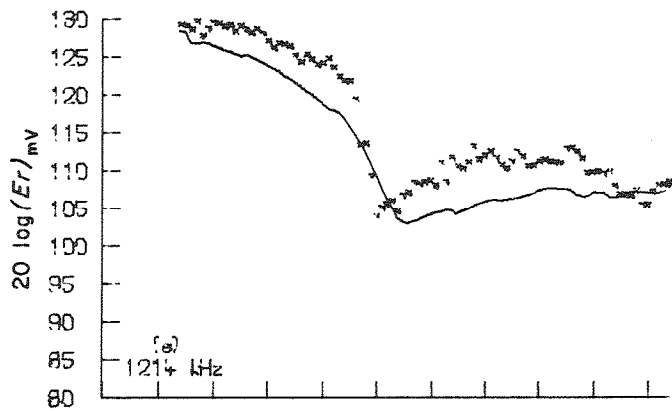
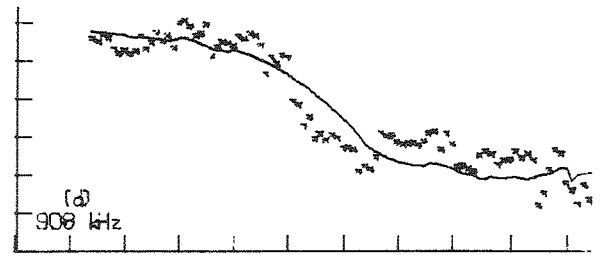
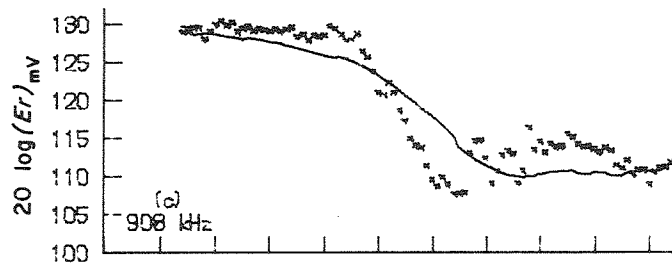
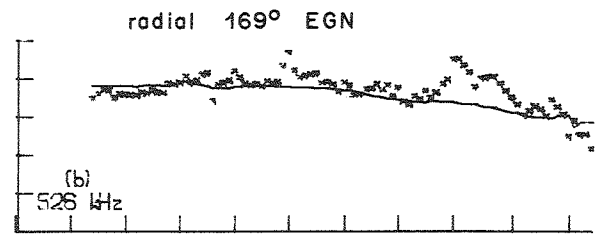
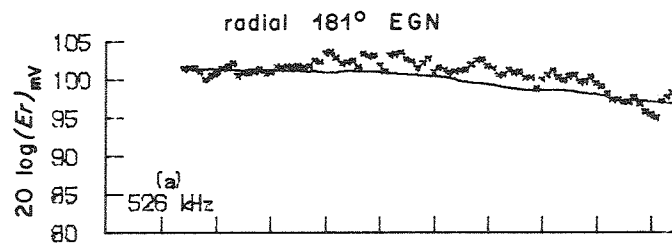


Fig. 13 - Comparison of measurements and predictions in London
 x Measured H field — Calculated H field

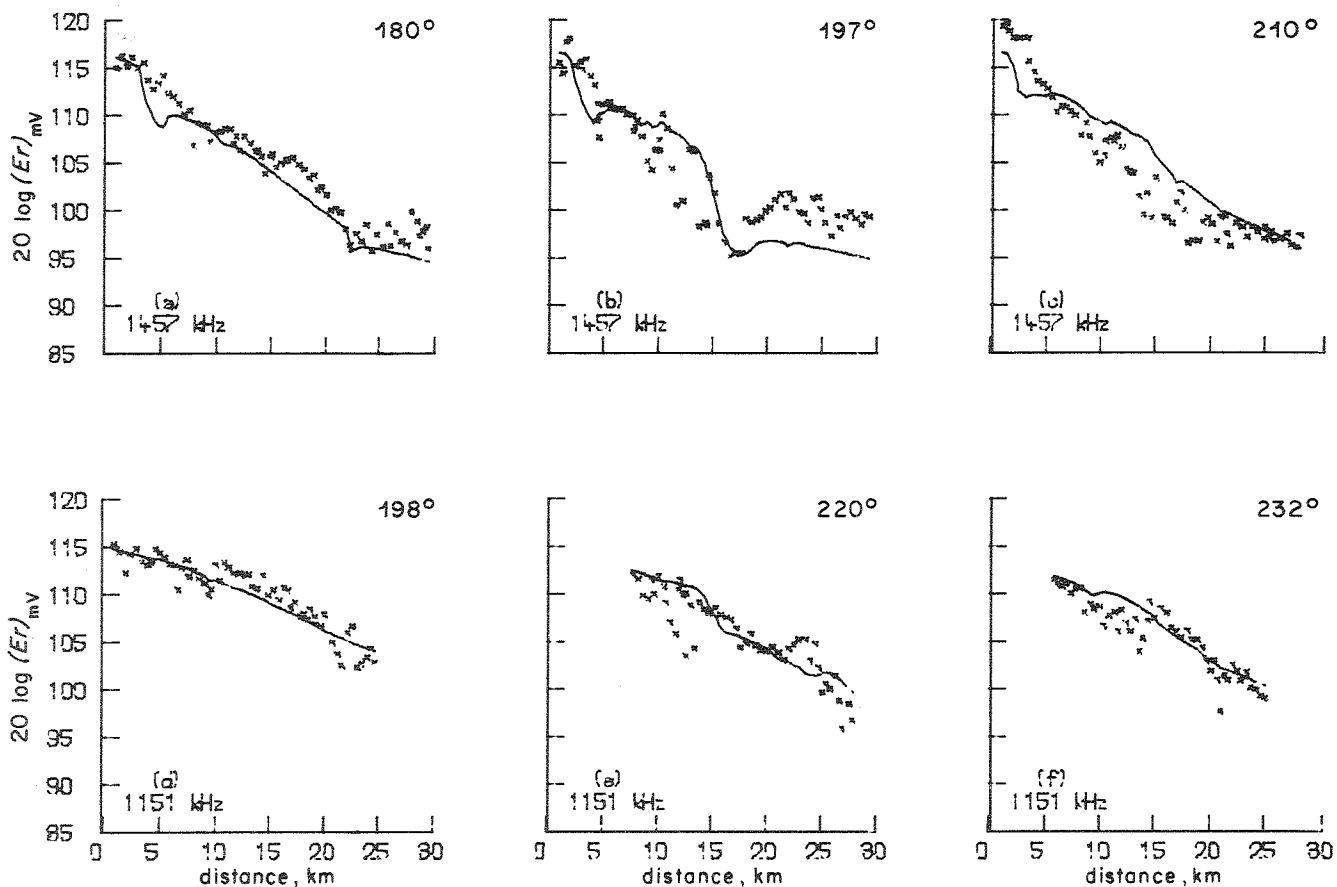


Fig. 14 - Comparison of measurements and predictions in Birmingham
 x Measured H field — Calculated H field



Fig. 15 - Comparison of measurements and predictions in the New Forest
 x Measured H field — Calculated H field

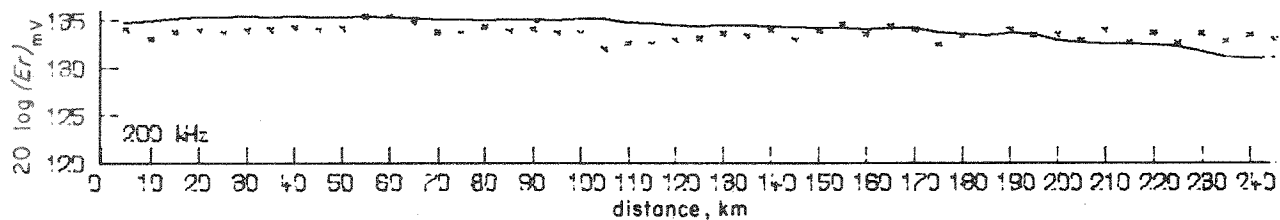


Fig. 16 - Comparison of measurements and predictions from Droitwich
 x Measured H field — Calculated H field

are reproduced with reasonable accuracy, much improved relative to results without the new clutter factors. However, we have sacrificed the possibility of greater accuracy for two reasons:

1. The simple clutter categories make preparation of data for the programs easier, cheaper and quicker.
2. The magnitude of the clutter term is restricted to keep results in a domain clockwise of a line, on Fig. 1, which is 51° from the origin. In the extreme examples of the high frequency end of the MF band and highly built-up areas larger angles can exist, but these cases are very sensitive to data accuracy and pass through a point of zero field.

The effect of our constraints is particularly noticeable on Fig. 13(c), but we consider the smoother calculated result to be preferable to a dramatic calculation in a case where it is not realistic.

Fig. 14 shows the Birmingham results, which were not used in the development of the prediction system. Again, the field trends are well reproduced. However, on Figs. 14(a)–(c) the calculations have a reduction at about 5 km, associated with the trees in Sutton Park, which

is greater than measured. This may be explained if these trees are less tall and dense than the values assumed in our category.

Fig. 15 shows the results from the Bartley transmitter indicating that a reasonable prediction is made for the effect of trees. In particular it may be noted that more attenuation of the magnetic field occurs on Fig. 15(b) beyond the 10 km range where there are more trees. Fig. 16 shows the results for the 200 kHz measurements from Droitwich to Hastings. In this case only the terrain undulation effect was allowed for in the calculation because it was considered to be the dominating influence on the field variation.

Table 2 gives some statistics of the differences between calculated and measured attenuations. There are some rather large errors in the electric fields which are due to particularly dense and tall buildings. We cannot expect accurate calculations in these cases when only using the simplified clutter data. To give an idea of the advantage of the system proposed we have calculated the same statistics for the Brookman's Park 1457 kHz transmission, on 169° , without using the new clutter factors. These figures are shown in brackets on the table. It can be seen the errors are much larger; this is despite the fact

TABLE 2

Statistics of differences between calculated and measured attenuations

Transmitter	Radial Bearing degree	Freq. kHz.	Magnetic Calc-Meas. (dB)			Electric Calc-Meas. (dB)		
			Mean	R.M.S.	Max.	Mean	R.M.S.	Max.
B.P.	181	526.5	-1.0	1.5	-3.2	-2.8	3.8	-6.7
B.P.	169	526.5	-0.8	1.9	-5.8	-2.0	4.1	-11.9
B.P.	181	908	-0.5	3.2	8.4	-2.6	4.5	-9.2
B.P.	169	908	-0.2	2.6	-4.2	-2.8	4.5	-11.7
B.P.	181	1214	-3.3	4.0	-7.9	-2.8	5.0	15.3
B.P.	169	1214	-0.4	2.4	5.3	0.1	4.5	20.6
B.P.	181	1457	-2.6	3.9	-8.0	-3.3	5.2	-10.1
B.P.	169	1457	0.0	2.5	7.3	-0.6	4.5	14.8
			(6.9)	(8.9)	(18.9)	(12.1)	(14.6)	(38.4)
S.C.	180	1457	-1.4	2.0	-5.4	-0.4	2.2	-3.6
S.C.	197	1457	-0.8	3.2	7.8	0.6	4.4	18.9
S.C.	210	1457	1.4	3.2	7.9	1.9	3.6	8.1
BRMB	198	1151	-0.2	1.3	-2.4	-0.3	1.6	3.6
BRMB	220	1151	0.7	2.3	5.0	1.4	3.3	8.4
BRMB	232	1151	0.9	1.8	4.6	0.5	2.3	6.9
Bartley	188	692	-0.5	1.4	-2.6	-0.9	2.0	-4.5
Bartley	214	692	-1.1	1.5	4.1	-1.0	2.2	-4.5
Droitwich	130	200	0.5	1.3	3.2	-0.7	1.8	-3.3

that we have allowed reduced conductivity values for the built-up areas.

5. Conclusions

The work described in Reference 1 has been extended to include trees and terrain undulations, both of which have been found to have a relevant modifying effect on propagation of ground waves. Many more measurements have been made to substantiate the theory and produce factors needed for calculations. Electric and magnetic fields have been measured and it has been shown that there may be large differences from the free space ratio.

The calculation system has been designed so that a prediction can be made easily; the necessity to choose heights and percentage of ground coverage is removed by having simple categories. The accuracy of the calculation is such that predictions can be made which are much better relative to the assumption of a smooth earth.

6. References

1. CAUSEBROOK, J.H. 1977. Ground-wave propagation at medium frequency in built-up areas. BBC Research Department Report No. 1977/25.
2. CAUSEBROOK, J.H. Medium-wave propagation in built-up areas. *Proc. IEE*, Vol. 125, No. 9, Sept. 1978, pp. 804 – 808.
3. CAUSEBROOK, J.H. Electric/magnetic field ratios of ground waves in a realistic terrain. *Electronics Letters*, Vol. 14, No. 19, Sept. 1978, pp. 614 – 615.
4. Terman, F.E. Radio Engineers Handbook. McGraw Hill, 1943, p. 709.
5. PAGE, H. 1963. An introduction to the theory of aerials. BBC Research Department Report No. E-085, Serial No. 1963/27, p.30.
6. WAIT, J.R. Guiding of electromagnetic waves by uniformly rough surfaces. Part 1, IRE Transactions on Antennas and Propagation. Vol. AP7 special supplement, Dec. 1959, pp. S154 – 162.
7. WAIT, J.R. Guiding of electromagnetic waves by uniformly rough surfaces. Part II, IRE Transactions on Antennas and Propagation. Vol. AP7 special supplement, Dec. 1959, pp. 163 – 168.